Influence of Heavy Gas Blowing into the Wall Layer of the Supersonic Boundary-layer on its Transition

S.A.GAPONOV, V.I.LYSENKO, B.V.SMORODSKY, YU.G.ERMOLAEV,
A.D.KOSINOV, N.V.SEMIONOV, A.A.YATSKIKH
Khristianovich Institute of Theoretical and Applied Mechanics
Novosibirsk, 630090
RUSSIA
gaponov@itam.nsc.ru http://www.itam.nsc.ru

Abstract: - The experimental investigation of the influence of the distributed blowing of heavy gas (sulfur hexafluoride, SF_6) into the wall layer of a supersonic boundary layer on a flat plate (at free stream Mach number M=2) on the laminar-turbulent transition have been performed. It is shown experimentally for the first time that in case of such blowing there is the boundary layer stabilization, and the laminar-turbulent transition is removed downstream from the model leading edge.

Key-Words: - **C**ompressible boundary layer, experimental, blowing, heavy gas, stability, transition

1 Introduction

In a number of tasks, the question arises about the boundary layer control. One of methods of such control is the gas suction from a boundary layer through a permeable surface which slowdown the turbulization process. The stabilizing role of suction is explained by the thickness reduction of a boundary layer and the formation of a more stable velocity profile. Methods of the flow stabilization (both at subsonic, and at supersonic speeds) are discussed in books [1, 2]. At the same time in researches on the boundary layer stability at the suction it is necessary to consider properties of permeable surfaces which can influence on the stability significantly. For the first time an influence of permeable covering properties on the subsonic boundary layer stability was investigated theoretically by Gaponov [3]. In the subsequent paper [3] he offered the impedance ratio between velocity and pressure perturbations on the permeable surface, taking into account the gas compressibility. It has been used for researches both for subsonic [3] and for low supersonic flows [4].

For a long time these theoretical works were single in the world, and experimental studies of this problem were not available at all that was caused first of all by lack of qualitative permeable materials. But now the situation has changed. In recent years experiments on stability both hypersonic [5-8], and a supersonic boundary layer were conducted [9-13]. Results of these experiments indicate on their satisfactory agreement with data of the linear theory [3-4] both for supersonic [9-13] and for hypersonic [14-15] speeds.

At researches of the laminar-turbulent transition and stability of a boundary layer, both in natural conditions, and at introduction of artificial disturbances [9-13], it was obtained that the porous coating accelerates a perturbations increase of a low frequency (the first mode) and destabilizes a boundary layer. However, calculations [16-17] showed that it is possible to stabilize a supersonic boundary layer by means of an injection of the heavy gas into the wall area.

This work is devoted to the experimental verification of these theoretical conclusions. The aim of this work is the experimental study of the influence of the heavy gas injection (sulfur hexafluoride, SF_6) in a supersonic boundary layer on its stability and the laminar-turbulent transition at Mach number M_∞=2.

2 Experimental technique

The experiments were performed in the supersonic wind tunnel T-325 of the Institute of Theoretical and Applied Mechanics of the Russian Academy of Sciences with the test section dimensions 600×200×200 mm at Mach number M=2, stagnation temperature $T_0 \approx 290^{\circ}$ K and unit Reynolds numbers $\mathrm{Re}_1 = U_e / \nu_e = (11 \text{ and } 6.6) \cdot 10^6 \, /m$; U_e, ν_e –the velocity and kinematic viscosity at the boundary layer edge.

The insulated flat plate was used as model (Fig. 1) which was made from stainless steel X18H9T. Its sizes were: long - 440 mm, thick - 10 mm and wide - 200 mm. The plate front was skewed at an angle14^0. The blunting radius of the front edge was about 0.05 mm.

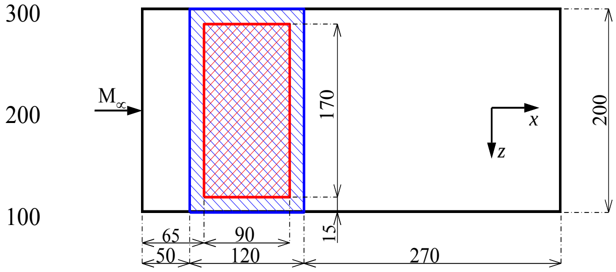
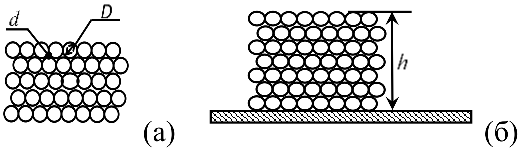


Fig. 1. The experimental model in the plan. All porous insert is marked with blue shading (x=50÷170mm), permeable its part is marked with red shading (x=65÷155mm).

The beginning of the longitudinal coordinate x (along the direction of an external flow) is on a leading edge of a model. On the section of a working surface x=50÷170mm (on the whole width of the plate) the groove was made in the model where the flat porous insert was inserted (a flush with the main model surface). The porous insert was made from stainless steel ПНС-8. Its properties were the following: the porosity - 39%, the filtration purity (an analogue of a pore size) -10μm, the thickness - 2.5mm, the surface roughness R_z≈11-12 μm. The surface roughness was measured by the optical profilometer (Zygo New View 7300). Structure of the porous inserts is shown in Fig. 2. According to the model construction, the permeable part of a porous insert settled down on the section x=65÷155mm and -85mm<z<. The plate was attached to side walls of the wind tunnel working rigidly and it was installed under a zero attack angle.



(a) (б)

Fig. 2. Schematic representation of porous inserts: plan view (a) cross-section (b).

If the working model was circulated in experiments by air, then as a gas which was injected in a boundary layer through a permeable surface was chosen the sulfur hexafluoride, SF_6. Molecular weight of this gas $m_1 = 146.07$ and its density at reference conditions is equal to 6.15 kg/m³, i.e. it is about 5 times heavier than air. Experiments were made for a different expense of the sulfur hexafluoride at its injection in a wall section of the boundary layer.

Measurement of a boundary layer transition location and its stability to natural perturbations were performed using the constant temperature anemometer (CTA) with the sensor from tungsten hot-wire which had the diameter equal to 10 μm and the long equal to 1.5mm. The sensor overheating value was equal to 0.8. Therefore it is possible to claim that pulsations of mass flow were fixed mainly.

Amplitude measurements of natural disturbances in the boundary layer were conducted in a location where there were the highest pulsations at constant E (E is an average voltage in a bridge diagonal of an anemometer) that correspond to the lines of a constant mass flow.

The pulsation and average characteristics of a flow were measured by means of the automated system of the data collection [18] which the wind tunnel of T-325 is equipped. The pulsation signal from a hot-wire anemometer is registered by 12-bit 750 kHz analog-to-digital converter. Length of realization was 65536 points. For monitoring of the results repeatability four measurements were carried out at each point. Mean voltage values from the hot-wire anemometer were measured by the digital voltmeter Agilent 34401A and entered into the computer. As a rule indications of average and pulsation characteristics of a flow were registered through each 2 mm on longitudinal coordinate x. Amplitude-frequency spectrum $A(f,x)$ was calculated as a result of the power spectra averaging, which was carried out on 101 points that there corresponded to a strip 1.1 kHz.

3 Flow Stability calculations

Dynamics of a binary mixture of viscous heat-conducting compressible gases is described by a common system of differential equations in partial derivatives which can find in [19, 20]. From these common equations authors of this paper obtained the system of equations in an approximation of a local self-similarity of a flow for a flow description in a two-dimensional (2D) stationary supersonic boundary layer of binary gases mixtures in an absence of chemical reactions [21]. These equations take into account diffusion, thermal diffusion and a longitudinal pressure gradient. The most important parameters that influence on a dynamics of the mixture are: m_2, m_1 -molecular weights and C_{p2}, C_{p1} - specific heat capacities of a main gas and an impurity, respectively and a impurity flow rate through a model surface: $f_w = \bar{\rho}_w \bar{V}_w \mathrm{Re}$, where $\bar{\rho}_w$ – mixture density on a wall the normalized at a density on external boundary layer edge, $\bar{V}_w$ – normal component of a velocity on the wall normalized at a velocity on external boundary layer edge, Re –Reynolds number constructed on Blasius's scale of a laminar boundary layer $\delta = \sqrt{\nu_e x / U_e}$. It is possible to see that the injection parameter actually is the normalized mass flow of the mixture through the permeable surface.

Calculations of viscosity and heat conductivity coefficients of components of binary mixtures and diffusion coefficients of an impurity were carried out within the kinetic theory [19] with use Leonard-Jones potential. To calculate the viscosity and thermal conductivity of a binary mixture the relations [23] have been used. For calculations of a thermal conductivity of polyatomic gases Eucken's correction [24] was taken into account also. The boundary layer equations of the binary gas mixtures was integrated numerically by means of the Runge - Кутта method of the fourth order. The equations, boundary conditions and numerical methods which were used in this paper are presented in more detail in [21].

The linear stability theory of boundary layers of binary mixtures was developed by authors of this paper and presented in [24, 25]. The linearization of the dimensionless equations of the viscous heat-conducting binary gas mixtures motion for quasi-harmonic on space and time disturbance of a view $q(x,y,z,t) = \tilde{q}(y) \exp i(\alpha x + \beta z - \alpha C t)$ reduces to the following system of ordinary differential equations:

$$i\alpha(\bar{U} - C)\tilde{\rho} + \frac{d\bar{\rho}}{d\bar{y}}\tilde{v} + \bar{\rho}\left(i(\alpha\tilde{u} + \beta\tilde{w}) + \frac{d\tilde{v}}{d\bar{y}} \right) = 0 \ ,$$

$$\bar{\rho}\left(i\alpha(\bar{U} - C)\tilde{u} + \frac{d\bar{U}}{d\bar{y}}\tilde{v} \right) = -\frac{i\alpha\tilde{p}}{\gamma_e \mathrm{M}_e^2} + \frac{\bar{\mu}}{\mathrm{Re}}\frac{d^2\tilde{u}}{d\bar{y}^2} \ ,$$

$$\bar{\rho} i\alpha\left(\bar{U} - C\right)\tilde{v} = -\frac{1}{\gamma_e \mathrm{M}_e^2}\frac{d\tilde{p}}{d\bar{y}} \ ,$$

$$\bar{\rho} i\alpha(\bar{U} - C)\tilde{w} = -\frac{i\beta\tilde{p}}{\gamma_e \mathrm{M}_e^2} + \frac{\bar{\mu}}{\mathrm{Re}}\frac{d^2\tilde{w}}{d\bar{y}^2} \ , \qquad (1)$$

$$i\alpha\left(\bar{U} - C\right)\tilde{c} + \frac{d\bar{c}}{d\bar{y}}\tilde{v} = \frac{\bar{\mu}}{\mathrm{Re}\,\mathrm{Sm}}\frac{d^2\tilde{c}}{d\bar{y}^2} \ ,$$

$$\bar{\rho}\left(i\alpha\left(\bar{U} - C\right)\tilde{h} + \frac{d\bar{h}}{d\bar{y}}\tilde{v} \right) = \frac{\gamma_e - 1}{\gamma_e} i\alpha\left(\bar{U} - C\right)\tilde{p} + $$

$$+ \frac{\bar{\mu}}{\mathrm{Re}\,\mathrm{Pr}}\frac{d^2\tilde{h}}{d\bar{y}^2} + \frac{\bar{\mu}}{\mathrm{Re}}\left(\bar{h}_1 - \bar{h}_2\right)\left(\frac{1}{\mathrm{Sm}} - \frac{1}{\mathrm{Pr}}\right)\frac{d^2\tilde{c}}{d\bar{y}^2} \ ,$$

where $\left(\tilde{u}, \tilde{v}, \tilde{w}, \tilde{h}, \tilde{c}\right)$ – disturbances of three velocity components, an enthalpy and an impurity concentration respectively; (α, β) – longitudinal and transversal wave numbers; $\omega = 2\pi f \delta / U_e$ – a nondimensional frequency; f – frequency in Hz; $C = \omega / \alpha$; $F = \omega / \mathrm{Re} = 2\pi f \mu_e / \rho_e U_e^2$ – frequency parameter.

The system (1) is solved with the following homogeneous boundary conditions on the surface and on the outer edge of the boundary layer:

$$\left(\tilde{u},\, \tilde{w},\, \tilde{h},\, f_w\tilde{c} - \bar{\rho}_w \bar{D}_{12}\frac{d\tilde{c}}{d\bar{y}} \right) = 0 \ \text{при}\ \bar{y} = 0 \ , \qquad (2)$$

$$\left(\tilde{u}, \tilde{w}, \tilde{h}, \tilde{c}\right) \to 0 \ \text{при}\ \bar{y} \to \infty$$

Integration of the eigenvalue problem (1-2) was carried out numerically with using of a orthogonalizations method. The numerical solution method of the stability equations is described in [1] in more detail. Stability calculations of the boundary layer of the binary gas mixture had been carried out investigated in [25].

4 Results

In this experiment the laminar- turbulent transition location on a flat plate was investigated in a dependence on the mass flow injected of the sulfur hexafluoride in a wall layer of a boundary layer.

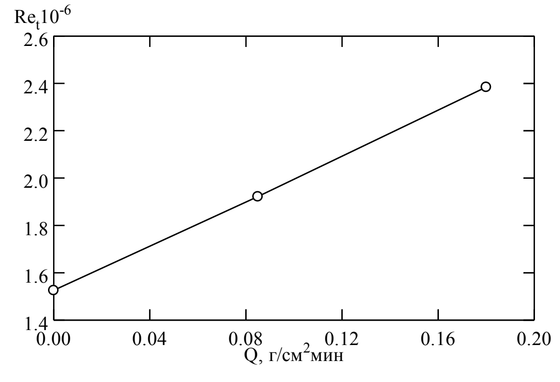


Fig. 3. Dependence of the transition Reynolds number on the mass flow of the injected sulfur hexafluoride

The transition Reynolds number was determined as $\mathrm{Re}_t = x\mathrm{Re}_1^*$, where Re_1^*– a unit Reynolds number at which the maximal value of a sensor signal of a anemometer was reached at x =140 mm. Experiments were made at three mass flow values of the blown sulfur hexafluoride: Q=(0, 0.085, 0.18) g/(cm^2·min.). The received results on the influence of such injection on the transition location at $\mathrm{Re}_1 = 11 \cdot 10^6 / m$ are shown in Fig. 3. From Fig. 3 it follows that transition Reynolds number increases with an increase of the sulfur hexafluoride expense.

At $\mathrm{Re}_1 = 6.6 \cdot 10^6 / m$ the natural disturbances development on a porous plate at Q=(0, 0.085) g/(cm^2·min.) and the solid plate was investigated experimentally. All these data were compared with calculations results in accordance with the linear stability theory.

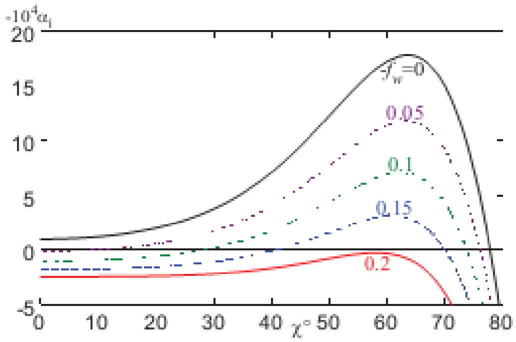


Fig. 4 Nondimensional spatial amplification rates α_i for 3D perturbations versus angle χ CCl_4, $\mathrm{Re} = 1100$, $F \cdot 10^6 = 25$.

It is known [2] that an amplification rate of disturbances depends on the transversal wave number β. For every one β there is a sliding angle χ=arctg(β/α_r). In Fig. 4 dependences of amplification rates on the sliding angle are shows at different values of the sulfur hexafluoride injection. It is possible to see, that maximal amplification of disturbances corresponds to the sliding angle χ≈60°. However in wind tunnels T-325 and others ones acoustic waves with the sliding angle χ ≈ 40° prevail [26]. Exactly therefore disturbances with χ ≈ 40° are generated in a boundary layer of a plate, that it was supported by calculations of the stability of the boundary layer on a smooth solid plate for the studied frequency range at a simple Reynolds number $\mathrm{Re}_1 = 6.6 \cdot 10^6 / m$. The best agreement of theoretical increase curves of disturbances with experimental data was reached at a slipping angle of disturbances relative to main flow χ=40°. This value χ was used in calculations of increase curves of disturbances in a boundary layer on a porous insert.

In Fig. 5 increase curves of amplitudes disturbances, *A=A (x)*, on longitudinal coordinate *x* (both the experimental, and calculated (χ=40°)) at $\mathrm{Re}_{1\infty} = 6.6 \cdot 10^6$ m^{-1} and f=10kHz for three cases are given: 0 – the solid smooth insert, 1 – the porous insert without an injection (Q=0), 2 – the porous insert with the sulfur hexafluoride injection (Q=0.085 g / (cm^2 min.)). Increase amplitudes are normalized on their value at x = 70 mm, $A(x = 70\mathrm{mm}) = 1$

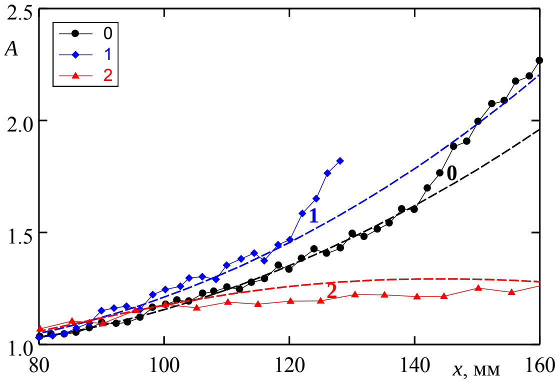


Fig. 5 Increase curves of disturbances amplitudes at the frequency *f*=10 кГц по продольной координате. $\mathrm{Re}_{1\infty}$=6.6·10^6/m, calculation at *χ*=40° (dotted lines) and experiment (symbol), 0 – the smooth solid insert, 1 – the porous insert without an injection (*Q*=0), 2 – the porous insert with the sulfur hexafluoride injection, SF_6 (*Q*=0.085 g/(sm^{2}min.)).

From Fig. 5 it is visible the rather good agreement of calculations with experimental data. The deviation of the experimental curves from of the linear theory data indicates about a non-linear stage of a disturbances development and the beginning of a laminar - turbulent transition. This happens at x ≈ 140 mm on smooth solid plate (0), at x ≈ 120 mm on the model with the porous insert without blowing (1) and at *x*>160 mm on models with the sulfur hexafluoride blowing, Q = 0.085 g/(cm^{2}min) (2). Fig. 5 shows clear that without an injection the surface porosity destabilizes a supersonic boundary layer (M_∞=2) because of a roughness existence, but the heavy gas injection stabilizes it significantly, it becomes more stable even in comparison with the boundary layer stability on a smooth solid surface.

5 Conclusion

The experimental study of the influence of the distributed heavy gas (the sulfur hexafluoride, SF_6) blowing in a wall region of a boundary layer on a laminar-turbulent transition of a supersonic boundary layer at Mach number M_∞=2 was carried out for the first time. Experiments show that the heavy gas blowing stabilizes a supersonic boundary layer and increases the transition Reynolds number. The experimental data of disturbances amplitudes increase curves agree with theoretical results.

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